Article

Real Time Sustainable Power Quality Analysis of Non-Linear Load under Symmetrical Conditions

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Abstract: Voltage sag is one of the most significant power quality problems in the industry and has a significant impact on induction motor safety and stability. This paper analyzes the characteristics of voltage dips in power systems and induction motors with a special emphasis on balanced dips with the help of virtual grids (regenerative grid simulator), as per IEC 61000-4-11. Three phase induction motors with 3.3 kW, 16 A coupled to a DC generator with 3.7 kW, and 7.8 A rated are considered for the test analysis. This paper aids in the development of an induction motor to achieve improved precision by taking different voltage sags into account. The experimental results benefit the design modifications of induction motors at industrial and other commercial levels of consumers regarding major power quality issues and the behavior of the induction motors. A proposed modification employing ANSYS is provided to further examine the precise performance of induction motors during sag events.

Keywords: power quality; voltage sag; induction motor; grid emulator; ANSYS

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1. Introduction

Voltage sags are thought to be responsible for between 92–98 percent of all outages caused by power supply problems [1]. As a result, it's critical to precisely analyze the impact of voltage sags. In the conventional sag characterization technique, voltage sags are characterized by their magnitude and duration. During the sag, the magnitude is defined as a percentage of the remaining voltage (as shown in Figure 1). The duration of the sag in this example is the time between the start and end of the sag. In recent years, one of the most critical concerns that electrical engineers have been aware of is power quality. Various power quality issues, such as voltage sags, voltage distortions, voltage imbalances, and voltage fluctuations, are frequent in power systems, wreaking havoc on generators, transformers, and industrial and home loads [2,3]. The induction motor is one of the most common industrial loads that are affected by power quality issues. Using low-quality voltage to power induction motors results in additional losses, overheating, and a drop in efficiency.

Voltage sag is a common occurrence in transmission and distribution systems [4]. Short circuits, overloads, or the starting of powerful motors cause voltage sag, which is a short-term drop in the root mean square (RMS) voltage. Voltage sags are gaining popularity as a result of their negative impact on sensitive equipment. Even if the voltage dips below 90% of the specified voltage for more than a few cycles, such equipment can trip. Furthermore, voltage sags are caused by faults that occur hundreds of kilometers

away [5–8]. Even if the voltage sag is not as severe as an interruption, the overall damage caused by sags is larger than that caused by interruptions since there are much more voltage sags than interruptions.

Figure 1. Voltage sag.

2. Methodology to Test the Sag Conditions Analysis of Sag Conditions

2.1. Regenerative Grid Simulator

A regenerative grid simulator may be used to modify essential parameters in order to replicate a reliable distribution grid/network conditions and settings, as illustrated in Figure 2. In single and three phase modes, variations in voltage amplitude, frequency, voltage dips, and phase angle are all maintained [9–12]. Simulating balanced and unbalanced situations (three phases) is simple. This simulator also satisfies IEC regulatory requirements 61000-4-11, which is a requirement for the AC supply [13–15]. The measurement accuracy of the Regenerative Grid Simulator are: Voltage—0.2% + 0.2% F.S, Current (RMS)—0.4% + 0.3% F, Current (Peak)—0.4% + 0.6% F.S, and Power—0.4% + 0.4% F.S.

2.2. Computer Control

The graphical user interface (GUI) was created with the goal of making the regenerative grid simulator setup as easy as possible. The soft panel (GUI) is installed in a computer that also has data recording functions, allowing many measurements to be reported and saved at the same time.

2.3. Load

For the distribution network, there are three phases—3.3 kW, 16 A with a DC generator as a load with 3.7 kW, and a 7.8 A induction motor are connected. There is also a power analyzer/fluke, since electronic power conversion designs should have high accuracy measurements to analyze and explain the incremental efficiency gains in devices.

2.4. Measurement

A power analyzer or fluke was formerly used to take accurate measurements and display repeated oscilloscope and particular shot events, like turn on and transients. The Oscilloscope utilized was different. The measurement setup's complexity and configuration time are both decreased. The measurement accuracy for the power analyzer are: basic accuracy (50/60 Hz)—0.05% of reading and best power accuracy (50/60 Hz)—0.1% of reading.

Figure 2. Voltage sag testing setup.

2.5. Test Process

One of four types of communication interfaces (GPIB, RS232, USB, and LAN) is chosen initially for communication between the PC and the AC source. The communication protocol is entered into the main window after it is set. The voltage and frequency parameters, as well as the sinusoidal output waveform, should all be set to the proper values. Phase edit selection can be used to adjust the output voltage in three phases for ease of usage. Various power quality tests may be performed in the PC window, with the results being recorded using the power analyzer.

3. Analysis of Sag Conditions

Figure 3 represents the hardware experimental setup for analyzing the single-phase sag in one of three phases, and symmetrical voltage sags in an induction motor at different stages.

Figure 3. Experimental setup.

3.1. Regenerative Grid Supply with Voltage Sag

In order to meet the Micro Grid test standards, the 61,800 Regenerative Grid Simulator can simulate various test scenarios such as voltage distortion, frequency fluctuations, and so on. Most crucially, the 61,800 series product's regenerative functionality allows it to absorb power generated by the Discrete Generator (DG) on the micro grid and feed it back to the main grid as shown in Figure 4.

Figure 4. Voltage sag conditions in grid.

Figure 5 represents the voltage sag created in the regenerative simulator as per the IEC-61000 std through the soft panel. These sags are tested under 40%, 70%, and 80% dips, which are created and repeated a number of times in order to assess the behavior.

Figure 5. Voltage sag of (a) 40%, (b) 70%, and (c) 80%.

3.2. Induction Motor under Voltage Sag

Figure 6 represents the test setup of the DC generator-coupled induction motor when subjected to a single-phase sag in one of the three phases of the AC supply, which was created in the regenerative grid simulator. The tested results under loaded conditions with and without neutral connection are tabulated in Tables 1 and 2.

Figure 6. Voltage sag conditions in grid connected to induction motor under no load.

Table 1. Induction motor under loaded conditions [neutral connected].

S.No	Dip	I_R (A)	I_Y (A)	I_B (A)	Transient Current		
					I_R (A)	I_Y (A)	I_B (A)
1	80%	4.5	15.9	11.7	8	10.9	8.8
2	70%	3.4	10.6	8.3	4	10.5	8.3
3	40%	4.0	6.4	6.4	5.2	8.2	7.1

Table 2. Induction motor under loaded conditions [neutral not connected].

S.No	Dip	I_R (A)	I_Y (A)	I_B (A)	Transient Current		
					I_R (A)	I_Y (A)	I_B (A)
1	80%	4.6	9.7	8.0	7.0	7.0	7.0
2	70%	4.0	11.3	8.8	7.3	8.3	7.6
3	40%	4.7	16.9	12.4	7.8	15.2	11.4

Figures 7 and 8 represent the THD values of the current and voltage of the induction motor, respectively, during the single-phase sag conditions (neutrally connected) under no load conditions. Figures 9 and 10 represent the same motor under the same conditions, but under loaded conditions.

Figure 7. Current THD of induction motor under no load conditions [neutral connected].

Figure 8. Voltage THD of induction motor under no load conditions [neutral connected].

Figure 9. Current THD of induction motor under loaded conditions [neutral connected].

Figure 10. Voltage THD of induction motor under loaded conditions [neutral connected].

3.3. Three Phase Sag

Generally balanced (symmetrical) voltage sags are caused by three-phase faults anywhere in the system for any short duration [16–19], as shown in Figure 11. In this approach, with the regenerative grid simulator, the three-phase sag is created and fed to the DC generator-coupled induction motor and is shown in Figures 12–15. As discussed in Section 4, the test is carried out with neutral and without neutral connections under no load and full load conditions. The results obtained are tabulated in Tables 3 and 4.

Figure 11. Voltage sag conditions in grid connected to induction motor under loaded conditions.

Figure 12. Voltage sag conditions in grid connected to induction motor under loaded conditions.

Figure 13. Voltage sag conditions in grid connected to induction motor under loaded conditions.

Figure 14. Voltage sag conditions in grid connected to induction motor under loaded conditions.

Figure 15. Voltage sag conditions in grid connected to induction motor under loaded conditions.

Table 3. Induction motor under loaded conditions [neutral not connected].

3-Ph Induction Motor-DC Generator Unit Under Neutral Connection [Full Load Conditions]							
S.No	Dip	Phase Currents			Transient Current		
		I _R (A)	I _Y (A)	I _B (A)	I _R (A)	I _Y (A)	I _B (A)
1	80%	7.8	7.8	7.8	8.7	8.6	8.4
2	70%	9.2	9	9	18.8	9.2	7.9
3	40%	12.9	12.8	12.9	14.2	15.2	15.2

Table 4. IM-DC generator set under loaded conditions [neutral not connected].

3-Ph Induction Motor-DC Generator Unit Under Neutral Connection [Full Load Conditions]							
S.No	Dip	Phase Currents			Transient Current		
		I _R (A)	I _Y (A)	I _B (A)	I _R (A)	I _Y (A)	I _B (A)
1	80%	2.5	2.5	2.5	4.4	4.4	4.1
2	70%	2.3	2.3	2.3	4.7	4.6	4.3
3	40%	1.4	1.4	1.9	7.4	6.9	5.9

Figure 16 represents the three-phase symmetrical voltage sag at 40%, 70%, and 80% when fed to a three phase—3.3 kW and 16 A with a DC generator as a load via a regenerative grid simulator. The measurement summaries are given below:

Figure 16. Grid connected to induction motor under loaded conditions with a sag of (a) 40%, (b) 70%, and (c) 80%.

Voltage (Nominal): 239 V

Current (Nominal): 40 A

Frequency (Nominal): 50 Hz

Number of events: Normal: 2, Detailed: 12

Power measurement method: Unified

Type of cable: Copper

Harmonic scale: %H1

Mode of THD: THD 40

DPF mode/Cos φ : Cos φ

Table 5 represents the symmetrical sag test on a three phase, 415 V, 5 Hp, 7.8 A induction motor when delta connected under loaded conditions, and star connected under loaded conditions with and without neutral connections, respectively.

Table 6 represents the results of star connected(non-neutral) three phase—7 kW, 7.8 A induction motor under loaded conditions, which are tested with a 40%, 70%, and 80% sag. Under 40% sag, the load can be maintained up to 2.8 kg, which leads to a huge rise of the line current. Under 70% sag, the load can be maintained up to 3 kg, which leads to a huge rise of the line current. Under 80% sag, the load can be maintained up to 3.2 kg, which leads to a huge rise of the line current.

Table 7 represents the results of star connected (neutral) three phase—3.7 kW, 7.8 A induction motor under loaded conditions, which are tested with a 40%, 70%, and 80% sag. Under 40% sag, the load can be maintained up to 2.1 kg, which leads to a huge rise of the line current. Under 70% sag, the load can be maintained up to 2 kg, which leads to a huge rise of the line current. Under 80% sag, the load can be maintained up to 2.4 kg, which leads to a huge rise of the line current.

Table 5. Delta connected three-phase induction motor under loaded conditions.

S.No	Dip	Line-Line Voltages			Phase Currents			Speed (rpm)	Weight S (Kg)	Torque T (N-m)
		V _{RY} (V)	V _{YB} (V)	V _{BR} (V)	I _R (A)	I _Y (A)	I _B (A)			
1	0%	414	417	414	3.4	3.4	3.8	1498	0	0.00
2		410	415	410	3.2	3.2	3.7	1498	0	0.00
3		415	416	414	3.5	3.3	3.6	1498	0	0.00
4		415	416	413	3.7	3.5	3.7	1490	3.2	4.71
5		413	414	411	4.1	4.1	4.2	1486	5.2	7.65
6		413	414	412	4.3	4.3	4.4	1480	7.1	10.45
7		413	414	411	5	4.8	5	1472	9.4	13.83
8		412	414	410	5.3	5.3	5.5	1468	10.8	15.89
9	40%	249.1	249.1	247.3	1.5	1.3	1.5	1498	0	0.00
10		250	247	248.7	1.5	1.8	1.5	1496	0	0.00
11		252	253	251	2	1.5	2.2	1486	2.6	3.83
12		251.4	252.1	250.3	2.5	1.8	2.6	1478	3.6	5.30
13		250.6	251.5	249.6	3.1	2.5	3.2	1470	4.5	6.62
14		249.7	250.5	248.3	3.4	2.8	3.5	1464	4.8	7.06
15		249.1	249.9	248.1	4	4.1	4.1	1454	5.5	8.09
16		247.8	248.8	247.3	4.5	4.3	4.5	1442	7	10.30
17		242.8	243.7	241.7	4.5	4.6	4.6	1436	7.1	10.45
18	70%	290	288	288	1.6	1.8	1.6	1498	0	0.00
19		290.3	289.7	287.7	1.8	1.6	1.8	1497	0	0.00
20		288.6	289.1	286.6	2	1.2	2	1492	2.1	3.09
21		287.8	286.9	285.9	2.5	1.6	2.6	1484	3.2	4.71
22		286.7	285.7	284.5	2.8	2.3	2.7	1476	4.3	6.33
23		285.9	285.4	284.2	3.5	3.1	3.5	1466	5.9	8.68
24		285	284.6	283.4	3.4	3.6	3.8	1458	6.9	10.15
25		283.7	283.8	282	4.6	4.6	4.6	1454	7.8	11.48
26	80%	331.6	331	331	2.1	2	2.3	1498	0	0.00
27		331	330	328.3	2.2	1.5	2.2	1496	0	0.00
28		330.4	329.5	328.1	2.4	1.6	2.3	1492	1.7	2.50
29		329.3	328.8	327	2.8	2.1	2.6	1488	2.9	4.27
30		328.8	328.5	326.4	2.7	2.5	2.7	1486	3.4	5.00
31		328.2	327.5	325.7	3.4	3	3.3	1480	4.7	6.92
32		327.4	327.4	325.2	3.7	3.5	3.7	1476	5.4	7.95
33		326.8	326.8	324.4	3.8	3.7	3.8	1468	6.6	9.71

Table 6. Star connected (non-neutral) three-phase induction motor under loaded conditions.

S.No	Dip	Line-Line Voltages			Phase Currents			Speed (rpm)	Weight S (Kg)	Torque T(N-m)
		V _{RY} (V)	V _{YB} (V)	V _{BR} (V)	I _R (A)	I _Y (A)	I _B (A)			
1	0%	415	417	414	0.4	0.5	0.5	1498	0	0.00
2		414	416	412	0.7	0.7	0.7	1484	2.5	3.68
3		414	415	412	1.7	0.6	1.6	1472	4.2	6.18
4		413	414	411	2.2	1.5	2.2	1456	6	8.83
5		412	414	412	2.8	2.4	2.4	1432	7.2	10.59
6		411	413	410	3.8	3.6	4.1	1398	9.4	13.83
7		411	413	411	4.7	4.7	4.7	1380	10.3	15.16
8		409	412	409	5.4	5.1	5.5	1324	11.6	17.07
9		408	411	408	5.9	5.6	6.1	1286	12.6	18.54
10	40%	249	248.7	247.5	0.2	0.1	0.1	1494	0	0.00
11		246.7	245.9	245.2	1.4	0.4	1.2	1450	2.4	3.53
12		246.1	245.1	244.4	1.6	1.5	1.6	1432	3	4.41
13		247	246.7	245	1.9	1.5	1.6	1432	2.8	4.12

Table 6. Cont.

S.No	Dip	Line-Line Voltages			Phase Currents			Speed (rpm)	Weight S (Kg)	Torque T(N-m)
		V _{RY} (V)	V _{YB} (V)	V _{BR} (V)	I _R (A)	I _Y (A)	I _B (A)			
14	70%	289.5	289.7	287.5	0.1	0.1	0	1496	0	0.00
15		288.1	288.7	286.7	0.5	0.4	0.6	1468	2	2.94
16		288.3	288.9	287.2	0.6	0.4	0.3	1462	2.6	3.83
17		286.7	286.4	284.8	1.4	1.5	1.4	1456	2.8	4.12
18	80%	332	331.9	330.4	0.4	0.1	0.4	1498	0	0.00
19		330.6	331.2	329.6	1.2	0.2	0.6	1472	2.8	4.12
20		330.3	330.8	328	1.5	0.4	1.5	1466	3	4.41
21		329.5	331.1	329.7	1.5	0.4	1.5	1464	3.2	4.71

Table 7. Star connected (neutral) three-phase induction motor under loaded conditions.

S.No	Dip	Line-Line Voltages			Phase Currents			Speed (rpm)	Weight S (Kg)	Torque T (N-m)
		V _{RY} (V)	V _{YB} (V)	V _{BR} (V)	I _R (A)	I _Y (A)	I _B (A)			
1	0%	415	418	415	0.25	0.25	0.25	1494	0	0.00
2		414	417	415	0.5	0.3	0.6	1486	1.6	2.35
3		414	417	415	0.6	0.6	0.6	1480	2.8	4.12
4		413	417	414	0.6	0.6	0.5	1478	3	4.41
5		415	419	415	1.5	1.4	1.5	1472	3.2	4.71
6	40%	249	249.5	247.6	0	0	0	1492	0	0.00
7		248.1	248.7	246.8	0.3	0.3	0.3	1474	1.2	1.77
8		248.3	249.7	246.9	0.5	0.5	0.5	1464	1.6	2.35
9		248	249.9	246.6	0.8	0.8	0.8	1462	1.8	2.65
10		247.8	248.6	246.7	1	1	1	1458	2	2.94
11		248	248.9	246.5	1.1	1.1	1.1	1454	2.1	3.09
12	70%	290.4	291.7	288.1	0	0	0	1494	0	0.00
13		289.2	290.4	286.6	0.2	0.2	0.2	1480	1.2	1.77
14		289.2	291.4	287.9	0.5	0.5	0.5	1472	1.6	2.35
15		289.2	291.1	287.6	0.7	0.7	0.7	1470	1.9	2.80
16		288.7	291.2	287.7	0.8	0.8	0.8	1466	2	2.94
17		287.6	290.3	287.2	1	0.9	1	1546	2	2.94
18	80%	332	333.6	329.3	0.4	1	0.5	1492	0	0.00
19		331	331.6	328.8	0.5	0.6	0.5	1478	1.7	2.50
20		330.1	331.3	328	0.6	0.6	0.6	1472	2	2.94
21		328.9	330.3	328.1	0.8	0.8	0.8	1470	2.2	3.24
22		330	331	328.3	1	1	1.2	1466	2.4	3.53

4. Design Modifications of the Induction Motor Using ANSYS

The ANSYS is the most widely used tool in the industry for developing and analyzing electric motors. It enables for rapid and exact electromagnetic, thermal, and mechanical analysis of an electric machine over its complete operating range (Figure 17). This product was designed and manufactured in close collaboration with competent electric machine designers. This design carried out in the ANSYS simulation on the basis of the standard parameters of the induction motor and the properties of the modelled induction machine are mentioned below:

(a) Machine Geometry **Figure 17.** 3-D design of Stator and Rotor.

Stator parameters

Slot Number: 18

Stator Lamination Diameter: 130

Stator Bore: 80

Width of Tooth: 7

Depth of Slot: 18

Tip depth of Tooth: 1

Slot opening: 3

Tip angle of Tooth: 30

Rotor Parameters

Rotor Bars: 26

Pole Number: 4

Bar opening and Depth [T]: 1.5

Bar Tip angle [T]: 20

Rotor Tooth Width [T]: 4

Bar Depth [T]: 10

Bar Connections Radius [T]: 1.33

Air gap: 1

Shaft Dia: 25

(b) Input Data (Materials)

Figure 18 represents the database of the materials, which are mostly chosen, and an update of this database is also available. Below are the properties of the materials and the weights on which the cost estimates can be based if the price per unit is known.

(c) Machine Winding

Figure 19 represents the winding of the induction motor, and the properties are mentioned below:

Lap winding: 50 turns

Throw: 4

Parallel paths: 1

Winding Layers: 2

Path type: Central

Component	Material from Database	Electrical Resistivity	Temp Coef Electrical Resistivity	Magnet Br at 20°C	Magnet Relative Permeability	Temp Coef Br	Density	Weight
Units		Ohm.m		Tesla		%/°C	kg/m ³	kg
Stator Lam (Back Iron)	M350-50A ☐	4.4E-07	0				7650	1.405
Stator Lam (Tooth)	M350-50A ☐	4.4E-07	0				7650	1.248
Stator Lamination [Total]								2.653
Armature Winding [Active]	Copper (Pure) ☐	1.724E-08	0.003862				8933	0.3745
Armature EWdg [Front]	Copper (Pure) ☐	1.724E-08	0.003862				8933	0.2493
Armature EWdg [Rear]	Copper (Pure) ☐	1.724E-08	0.003862				8933	0.2493
Armature Winding [Total]								0.8732
Slot Wedge	☐	0	0				1000	0.01224
Rotor Lam (Back Iron)	M350-50A ☐	4.4E-07	0				7650	0.9791
Rotor Lam (Tooth)	M350-50A ☐	4.4E-07	0				7650	0.719
Rotor Lamination [Total]								1.698
Rotor Cage Top Bar	Aluminium (Cast) ☐	3.3E-08	0.00375				2950	0.2548
Rotor Cage Top Bar Opening	Aluminium (Cast) ☐	3.3E-08	0.00375				2950	0.01558
Rotor Cage (Front End)	Aluminium (Cast) ☐	3.3E-08	0.00375				2950	0.09404
Rotor Cage (Rear End)	Aluminium (Cast) ☐	3.3E-08	0.00375				2950	0.09404
Rotor Cage								0.4585
Shaft [Active]	☐	0	0				7800	0.3446
Shaft [Front]	☐	0	0				7800	0.3637
Shaft [Rear]	☐	0	0				7800	0.2489
Shaft [Total]								0.9572
Total								6.653

Figure 18. Different material database for design.

Figure 19. Induction Motor Winding.

5. Simulation Results

For any motor type, the analytic single load point and no-load point tests are automatically computed. Torque speed/breakdown torque/locked rotor only AC mains (voltage driven) situations have characteristics/acceleration. Figure 20 represents the (a) speed vs. RMS current, (b) speed vs. torque, (c) speed vs. losses, and (d) speed vs. power characteristics of the induction motor with the suggested design modifications.

Figure 20. (a) Speed vs. RMS Current, (b) Speed vs. Torque, (c) Speed vs. Losses, and (d) Speed vs. Power.

6. Conclusions and Future Scope

This paper aids in the development of an induction motor to achieve improved precision by taking different voltage sags into account. Suggested modifications in the design parameters using ANSYS are provided to further examine the precise performance of induction motors during voltage sag events. Since balanced voltage sag is the major sag event, this study focuses solely on this mechanism. The experimental results benefit the design modifications of induction motors at industrial and other commercial levels of consumers regarding major power quality issues and behavior of the induction motors. This paper analyzes the characteristics of voltage dips in power systems and induction motors with a special emphasis on balanced dips, with the help of the virtual grid (regenerative grid simulator) as per IEC 61000-4-11. With regards to future study, the design modifications corresponding to each voltage sag process supports the industrial and other commercial levels of consumers.

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